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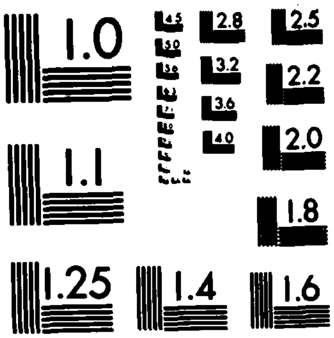

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SYNCHRONOUS GENERATORS WITH SUPERCONDUCTIVE EXCITATION WINDINGS

by

W. Paszek and A. Rozycki

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SYNCHRONOUS GENERATORS WITH SUPERCONDUCTIVE EXCITATION WINDINGS

Wladyslaw Paszek and Adam Rozycki

The article presents possibilities for taking advantage of superconductivity in the design of synchronous generator windings. Parameters of designed and built experimental models are listed. The concept of the structure of a synchronous generator with a superconductive excitation winding is discussed and specific characteristics of its design are presented. It is shown that an increase in magnetic induction and elimination of the ferromagnetic from the magnetic circuit allows one to reduce the dimensions, weight, and cost of the machine.

An increase in rated power of turbogenerators reduces operating and investment costs entailed in generating electric energy. Installation of turbogenerators with rated powers equal to 10% of the installed power in the system is permissible for exploitation of the power system. In the Polish power system, the admissible rated power of a turbogenerator is in excess of 1000 MW. Power systems are capable of incorporating generators with greater powers than the limiting powers of turbogenerators produced currently by the electric machine industry [1].

In industrially advanced countries the unit power of synchronous generators doubles over a period of 7 to 10 years. It can be assumed that if the rate of growth will not change, the unit power of synchronous generators will increase to 2 GW (or even greater power) in the nearest future. The limiting

power of bipolar synchronous generators (with a conventional structure) is 1200 MW. This power follows from the limitations on the dimensions of the machine because of the mechanical strength of the rotor and the limited induction caused by saturation of ferromagnetic sheets and the rotor forging. Increased utilization of active materials by increasing the specific current loading of the stator and rotor also encounters limitations resulting from heat-ventilating conditions.

Application of a grooveless (smooth) turbogenerator stator design makes it possible to increase the maximum induction in the air gap to the limiting value 2 T. Such induction requires a considerable increase in specific electric loading of the rotor, which entails an increase in losses and the necessity of increasing the cooling rate of the rotor.

Utilization of superconductors for excitation windings creates new development possibilities in electric machinebuilding, in particular, in the building of high-power synchronous generators. Although the superconductivity phenomenon has been known for more than 60 years, only the discovery of type II superconductors made it possible to take practical advantage of superconductivity in the structure of coils exciting strong magnetic fields. By obtaining working induction on the order of magnitude 5 T in an electric machine, practically without losses in the excitation winding, it is possible to eliminate completely or at least partially the ferromagnetic circuit.

1. Superconductive Materials Used for Excitation Windings in Electric Machines

The phenomenon of superconductivity involved decay of resistivity during cooling of a current conductor to the appropriate critical temperature T_k.

This means that losses resulting from the flow of electric current do not occur in a superconductor. However, in the loss balance one must take into account the expenditure of energy required for abstraction of heat losses by cooling equipment which occurs as a result of the imperfect heat insulation of the cryostat unit in which the superconductive winding is situated. Apart

from the critical temperature T_k, the superconductive state depends on the critical magnetic temperature H_k permeating the superconductor and also on the critical current flow in the superconductor I_k.

Superconductivity decay occurs when one of the critical parameters is exceeded.

In type I superconductors the magnetic field permeates insignificantly inside the superconductor as long as the magnetic field intensity is lower than the critical magnitude. When the magnetic field strength exceeds the magnitude H_k, superconductivity is destroyed.

Because for type I (so-called soft) superconductors (lead, niobium) the magnitude of the magnetic field intensity is very small, these superconductors are not suitable for windings in electric machines. Instead, they are used in other machine elements as materials for magnetic shields, parts in jet pumps, which utilize their advantageous properties (smaller losses in variable magnetic field than in type II superconductors).

Superconductors type II (so-called hard superconductors), namely, niobium and zirconium alloys NbZr, niobium and titanium alloys NbTi, and niobium and tin compounds Nb_3Sn, retaining superconductivity at considerably greater magnetic field intensities H_k, have been applied to generate strong magnetic fields.

Basic properties of these superconductors are presented in Table I.

Superconductors type II have a defect which limits their application in windings subjected to the effect of a flux or alternating current. A variable magnetic field causes the occurrence of losses to eddy currents and hysteresis which are proportional to the magnetic induction and frequency. Because superconductors are characterized by small specific heat and negligible heat conductivity, the heat losses arising in the superconductor which are not abstracted cause local heating and loss of superconductivity. The limited application of the superconductors in electric machines for excitation windings supplied with direct current follows from the above.

Table I. Basic Properties of Superconductors Type II

(a) Materiał	(b) Temperatura krytyczna T_k [°K]	Krytyczna indukcja (c) magnetyczna B_k [T]	Krytyczna gęstość prądowa j_k [A/mm²] przy 4,2 [°K] (d) $B = 5$ [T]
NbTi	9,5	12	2×10^3
NbZr	11	8	2×10^9
V_3Ga	14	20	10
Nb_3Sn	18,5	22	10^4

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Key: a. Material
b. Critical temperature, T_k (°K)
c. Critical magnetic induction, B_k (T)
d. Critical current density, j_k (A/mm²) at 4.2°K, B = 5 (T)

Besides the direct-current supply, these superconductors are also exposed to loss of superconductivity as a result of the effect of the variable component of the armature reaction flow, in particular, the component of the field with the opposite sequence, or as a result of the effect of the variable component in the direct supply voltage of the excitation winding. The entire excitation winding is protected from the variable component of the armature reaction flow by conducting shields attenuating the variable magnetic field permeating through the winding.

For the purpose of protecting the superconductor from destruction as a result of local superconductivity loss, heat stabilization of the superconductor is used, involving the use of a coating which is a good conductor of electricity and heat, such as copper, silver, or aluminum. Advantage is taken here of the difference in resistivity occurring between the superconductor and the stabilizing coating. When a normal conductivity zone arises in the superconductor, its resistivity increases considerably compared to the resistivity of the coating, which causes current displacement to the stabilizing coating. Because the ratio of the surface of a section of the coating to the surface of a section of the superconductor is greater than unity, the losses occurring in the coating are

reduced. After abstraction of the generated heat by the cooling system and elimination of the cause bringing about the appearance of a normal conductivity zone, the current passes back from the coating to the superconductor.

The measure of stabilization is defined by the ratio $F_{coating}/F_{supercond}$, which lies in the range 2—4.

The NbTi alloy turned out to be most advantageous for the excitation winding structure of synchronous machines, even though it does not exhibit the highest magnitude T_k, H_k, I_k among superconductors available in the market. The advantage of the NbTi alloy is its great ductility, which makes it possible to obtain superconductive fibers with diameter $5 \cdot 10^{-6}$ m. Superconductors used at the present time for winding structures consist of a large quantity of stranded fibers placed in a stabilizing coating.

Table II presents for illustration purposes the types of superconductors used in some experimental models and synchronous machine design.

Fig. 1 presents the graph of j = f(B) for the SUPRA NT7 superconductor (GDR) for two different operating temperatures T = 4.2°K and T = 7°K.

This superconductor is made in the form of a cable with a 1 mm diameter consisting of seven Nb_{48}%-Ti superconductor filaments, each with a 0.2 mm diameter stabilized with copper.

2. Cryogenic Fluids and Structural Materials

Selection of the coolant of the excitation winding is conditioned, above all, by the critical temperature of the superconductor. For superconductors that have been discovered so far, only liquid or gaseous helium can be considered. The recently discovered niobium-aluminum-germanium $Nb_{0.79}(Al_{0.73}Ge_{0.27})_{0.21}$ superconductor, whose critical temperature is T_k = = 20,7 °K, is on the helium temperature boundary. A superconductor which could be used in combination with liquid hydrogen must have a critical temperature of at least 25-30°K.

Table II. List of Superconductors Used in Some Experimental Models and Synchronous Machine Designs

Country	S_N	Type of superconductor	Superconductor structure
United States-AVCO-EVERETT model 1966	8 kW	$Nb_{48\%}$-Zr	fiber with 0.254 mm diameter stabilized with copper
United States-MIT (Massachusetts Institute of Technology) model 1969	80 kVA	Nb-Ti	fiber with 0.254 mm diameter stabilized with copper
United States-MIT + EDISON model 1973	2.1 MVA	$Nb_{48\%}$-Ti	rectangular conductor, dimensions 3.17X1.27 mm, consisting of 24 fibers with 0.254 mm diameter in a copper coating $F_{coating}/F_{supercond} = 2.6$
United States-MIT 1971 design	1000 MW	Nb-Ti	strip, thickness 17X0.127 mm stabilized with aluminum
USSR Academy of Sciences, Leningrad, model 1972	18 kW	Nb-Zr-Ti (65 B T)	cable wound with indium consisting of six fibers with 0.25 mm diameter and one copper fiber with the same diameter
USSR-ELEKTROYAZhmash, model 1971	200 kW	CC-2	cable consisting of eight fibers with 0.35 mm diameter
GDR-Ilmenau Institute of Technology, model 1971	10 kVA	$Nb_{48\%}$-Ti	cable with 1 mm outer diameter consisting of seven fibers with 0.2 mm diameter
ANGLIA-GEC, 1973 design	660 MW	$Nb_{44\%}$-Ti	cable consisting of 1525 fibers with 0.05 mm diameter in copper and nickel coating $F_{coating}/F_{supercond} = 4$

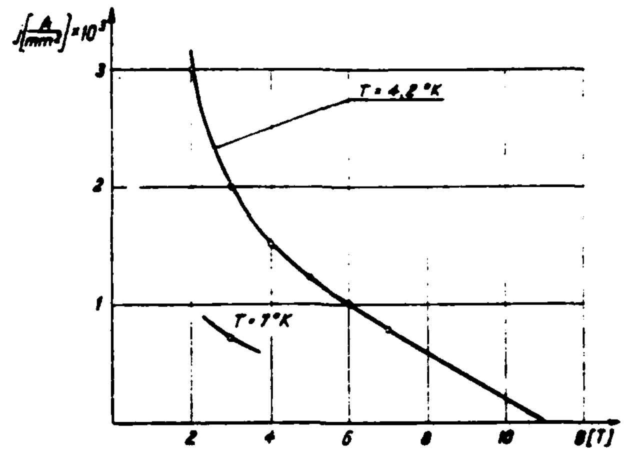

Fig. 1. Graph of j = f(B) at T = const for
SUPRA NT7 superconductor manufactured in GDR

Table III presents characteristic physical properties of cryogenic fluids, helium He, hydrogen H_2, neon Ne, and nitrogen N_2 [2]. A comparison of the properties does not favor helium. It has the smallest vaporization heat, which is more than 10 times lower than that of hydrogen, which consequently increases the expenditure of this medium for maintenance of the operating temperature in the machine.

It has also the lowest electric strength. In addition, helium has other shortcomings (it is very expensive). The discovery of natural gas deposits in Poland with substantial helium content in the gaseous form will lower its price. Its condensation is also expensive because of the very low efficiency of the cooling equipment and its considerable cost.

Table IV presents the heat conductivity λ_{mean} and the minimum stress at the mechanical strength limit σ of various materials in the range 20-300°K used in low-temperature installations. The table also presents the values of the indicator σ/λ_{mean} characterizing materials operating in cryogenic fluids. Structural elements located in the low temperature zone should have a large σ/λ_{mean} indicator.

Table III. Characteristic Physical Properties of Cryogenic Fluids

(a) Oznaczenie	Jednostka (b)	He	H_2	Ne	N_2
Temp. wrzenia przy 760 mm Hg (c)	°K	4.215	20.39	27.09	77.34
Gęstość cieczy przy 760 mm Hg (°C) (d)	$\frac{g}{cm^3}$	0,125	0,07	1,206	0,808
Ciepło parowania przy temperaturze wrzenia (e)	$\frac{kWs}{kG}$	20,595	448,195	86,022	199,29
Ciepło parowania przy temperaturze wrzenia (f)	$\frac{kWs}{l}$	2,574	31,813	103,74	160,90
Ciepło właściwe cieczy przy 760 mm Hg (g)	$\frac{kWs}{kg\ deg}$	4,336	9,48	1,821	207
Ciepło właściwe gazu przy 760 mm Hg (h)	$\frac{kWs}{l\ deg}$	0,542	0,674	2,196	1,674
Objętość gazu przy 0°C i 760 mm Hg przy odparowaniu 1 litra (i)	l	700	788	1340	643
Wytrzymałość elektryczna (j)	$\frac{kV}{mm}$	0,5 (k) 0,3 (gaz)	2 (k) 2 (gaz)	—	1,5 (k) 1,0 (gaz)

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Key: a. Property
b. Unit
c. Boiling point at 760 mm Hg
d. Fluid density at 760 mm Hg (°C)
e. Vaporization heat at boiling point
f. Vaporization heat at boiling point
g. Specific heat of fluid at 760 mm Hg
h. Specific heat of gas at 760 mm Hg
i. Volume of gas at 0° C and 760 mm Hg during vaporization of 1 liter
j. Electric strength
k. (gas)

The linear expansion of all low-temperature zone elements (winding, supporting structures, insulation, fastening elements) should be nearly identical to avoid formation of mechanical stresses in them during cooling.

3. Present State of Structure of Synchronous Generator with Superconductive Excitation Winding

The first information about the possibility of designing a synchronous generator with a superconductive excitation winding dates back to 1962 [3].

Table IV. Mean Heat Conductivity λ_{mean} and Minimum Stress at Mechanical Strength Limit σ of Various Materials in the Temperature Range 20—300°K

Material	[W/m deg] 4÷300°K $\lambda_{śr}$ (a)	[kG/mm²] σ	$\left[\frac{kG \cdot deg}{W\ cm}\right]$ $\frac{\sigma}{\lambda_{śr}} \cdot 10^3$ (a)	(b) q [W/m²] przy: $\Delta y = 280$ deg, $l = 1$ cm, $p = 10$ kG/cm²
Miedź (c)	266	8,5	3.2	88000
Aluminium S 20	46	38,5	840	340
Stal nierdz. 18/8 (d)	5,1	105	2060	140
Stop tytanu 4 Al 4 Mn (e)	3,4	100	3020	92
Teflon	0.135	1,4	1040	270
Nylon	0,175	1,4	8000	35
Mylar	0.085	7	8250	34
Dacron Du Pont	0.085	14	16500	17
Nylon z tkaniną szklaną (f)	0,2	40	20000	14
Superizolacja z tkaniną szklaną < 10^{-5} mm sł. rtęci (g)	0,0005	0,01	2000	140
Izolacja proszkowa (h) > 10^{-5} mm sł. rtęci	0,0005	—	—	—

Key:

a. λ_{mean}
b. at
c. Copper
d. Stainless steel 18/8
e. Titanium alloy 4 Al 4 Mn
f. Nylon with fiberglass fabric
g. Superinsulation with fiberglass fabric < 10^{-5} mm Hg
h. Powder insulation > 10^{-5} mm Hg

At the present time, in particular, during the last 3 years, a number of publications appeared about projects and the results of tests of experimental generators. Currently, more than 10 models of machines with superconductive excitation windings have been designed in a very wide range of power from several kVA to 5 MVA and speed from 3000 rpm to 24,000 rpm. Table V presents characteristic data for these generators.

Fig. 2 presents a cross-section of a grooveless synchronous generator with a superconductive rotating excitation winding (power S_N = 2.1/3.07 MVA, designed in the Massachusetts Institute of Technology (MIT), United States).

A detailed description of the structure of the synchronous generator is available in [5].

Experimental units with moderate power were built in a vertical system, and a horizontal structure is used in larger machines.

Using as the classification criterion the place where the superconductive excitation winding is situated, synchronous machines can be subdivided into two groups:

a. with immovable superconductive excitation winding situated: outside rotating armature (A); inside rotating armature (B)

b. with rotating superconductive excitation winding situated: outside immovable armature (C); inside immovable armature (D).

The first versions of synchronous machines with superconductive excitation windings in the late 1960's favored the design of an immovable superconductive excitation winding (A, B). The latter was related to lack of experience in the design of rotating cryostats and the fear of loss of superconductivity in the case of disturbances in the superconductive winding cooling system. This form of structure, which is appropriate for low-power machines, requires for large machines suitable current collector structures, which make it possible to transmit to the outside high-intensity, high alternating-voltage currents.

A system with a rotating superconductive excitation winding situated inside the armature (C) was abandoned, since it requires a substantially stronger exciting flow and hence a greater expenditure of superconductor energy. In addition, this form of structure requires a heavy external yoke or shield for enclosing or limiting the flux space. However, this would be a superconductive shield in which no losses would occur in view of the constancy of the flux, in contrast with external shield versions (D) of the generator.

In this form of structure, difficulties occur in the design of armature windings in the relatively small volume available inside the machine, while

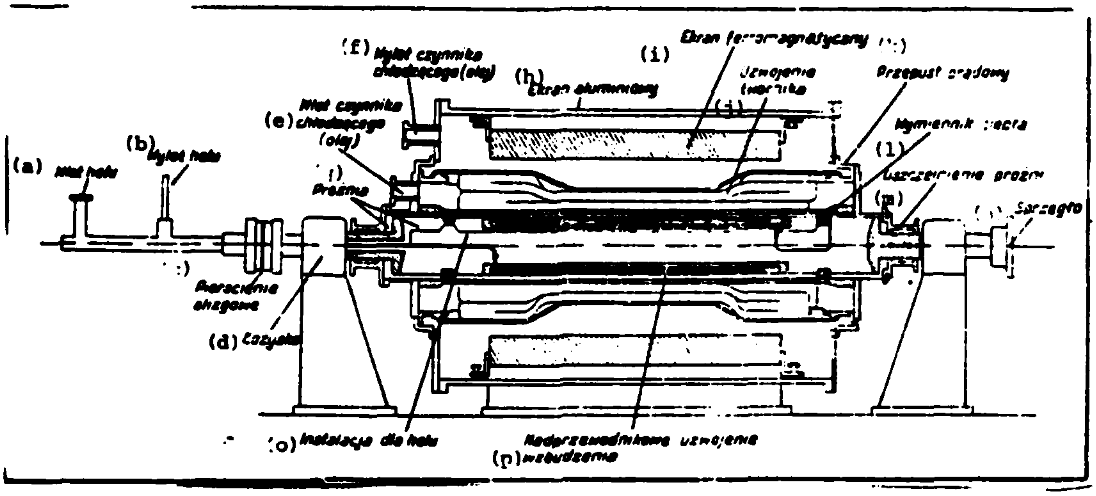

Fig. 2. Cross-section of grooveless synchronous generator with superconductive rotating excitation winding, power S_N = 2.1/3.07 MVA, designed in Massachusetts Institute of Technology (MIT), United States

Key:

a. Helium intake	g. Vacuum	l. Heat exchanger
b. Helium outlet	h. Aluminum screen	m. Vacuum seal
c. Slip-rings	i. Ferromagnetic shield	n. Coupling
d. Bearing	j. Armature winding	o. Helium installation
e. Coolant intake (oil)	k. Current seal wire	p. Superconductive excitation winding
f. Coolant outlet (oil)		

Table V. Characteristic Data for Experimental Models of Synchronous Generators with Superconductive Excitation Windings /4,5/ (status in 1974) /Key on next page/

Lp. (a)	Kraj (b)	Miejsce (c)	Rok (d)	S_N	U_N [V]	n_N [obr/min] (e)	f_N [Hz] (f)	Układ pionowy P_n poziomy P_z (g)	Forma budowy *) (h)	Parametry uzwojenia wzbudzenia (i): $j_{wz}\left[\frac{A}{mm^2}\right]$ (j)	B_{wz} [T] (k)	Typ nadprzewodnika (l) (m)	Parametry uzwojenia twornika: $j_{wo}\left[\frac{A}{mm^2}\right]$ (j)	B_{wo} [T] (u)	(n) Materiał na uzwojenie twornika
1	USA	AVCO-EVERETT US ARMY	model 1965	17,6 kVA	435	12000	400	P_n	B	150	15	Nb-Zr ciekły hel (o)	0,37	5	Cu (p) chłodzenie powietrzem
2	USA	AVCO-EVERETT US ARMY	model 1966	8 kW	250	12000	400	P_n	B	100	15	Nb-Zr ciekły hel (o)	—	2,5	Cu (p) chłodzenie powietrzem
3	USA	DYNATECH CORPORATION	model 1966	6.1 kW	500	12000	200	P_z	D	—	10	Nb_3Sn hel gaz (q)	—	—	Nb_3Sn (r) chłodzenie hel gazowy
4	USA	MIT	model 1969	80 kVA	50,25	3600	60	P_n	D	128	3	Nb-Ti ciekły hel (o)	1	—	Cu (p) chłodzenie powietrzem
5	USA	MIT-EDISON E.I.	model 1973	2.1 MVA / 3.07 MVA	950 1300	3600	60	P_z	D	125	3	Nb-Ti ciekły hel (o)	2,5	—	Cu (s) chłodzenie olejem
6	USA	WESTINGHOUSE	model 1973	5 MVA	4160	3600	60	P_z	D	—	5	Nb-Ti ciekły hel (o)	—	—	—
7	USA	WESTINGHOUSE	model 1973	8 MVA	5000	12000	400	P_z	D	—	5	Nb-Ti ciekły hel (o)	—	—	Cu (p) chłodzenie olejem
8	(bb) ZSRR	A. N. LENINGRAD	model 1969	~ 3 kW	—	3000	50	P_n	D	—	—	nadprzewodn. hel. alum. (t)	—	(t)	nadprzewodn. lub aluminium
9	(bb) ZSRR	ELEKTROTJAŻMAŚ CHARKÓW (dd)	model 1971	300 kW	—	3000	50	P_z	D	—	—	CC? (v) hel ciekły lub gazowy	—	—	Cu (w) chłodzenie hel gazowy
10	(bb) ZSRR	A. N. LENINGRAD	model 1972	10 kW	330	3000	50	P_n	D	—	—	Nb-Zr-Ti 65 BT (x)	—	—	Cu (y) chłodzenie ciekły azot
11	(bb) ZSRR	MOSKWA (ee)	model 1973	105 kW	380	3000	50	P_z	A	—	2.47	(z) nadprz.	6,2	1,8	Cu (aa) chłodzenie azotem
12	(cc) NRD	T. H. ILMENAU	model 1971	10 kVA	300	1500	50	P_n	B	80—130	~ 0,5	Nb-Ti Nb-Ti ciekły hel (o)	—	1,7	Cu (p) chłodzenie powietrzem

/Key to Table V/

a. Sequential number
b. Country
c. Place
d. Year
e. rpm
f. Vertical system P_n
g. Horizontal system P_z
h. Form of structure *)
i. Excitation winding parameters
j. j_{exc}
k. B_{exc} (T)
l. Type of superconductor
m. Armature winding parameters
n. Material for armature winding
o. liquid helium
p. air cooling
q. helium gas
r. gaseous helium cooling
s. oil cooling
t. superconductor or aluminum
u. B_{arm}
v. liquid or gaseous helium
w. gaseous helium cooling
x. 65 BT
y. liquid nitrogen cooling
z. superconductor
aa. nitrogen cooling
bb. USSR
cc. GDR
dd. Elektrotyazhmash, Kharkov
ee. Moscow

* A -- immovable superconductive excitation winding situated outside rotating armature
B -- immovable superconductive excitation winding situated inside rotating armature
C -- rotating superconductive excitation winding situated outside immovable armature
D -- rotating superconductive excitation winding situated inside immovable armature

ensuring appropriate cooling.

Mastery of problems related to the supply and draining of the cryogenic coolant to a rotating cryostat with a superconductive excitation winding, progress and the development of thermal insulation of cryostats in structural materials with a large σ/λ ratio made it possible to build machines with a

structure similar to that of conventional generators, i.e., with superconductive excitation winding situated inside an immovable armature (D).

In the light of the present state of engineering, the following machines have optimal realistic designs: a. with a horizontal structure; b. without a magnetic circuit from steel; c. with a rotating superconductive excitation winding cooled by liquid or gaseous helium; d. with smooth-core armature winding, situated outside the rotating excitation winding; e. with armature winding made from copper; f. with conductive attenuating shield situated between the excitation winding and armature; g. with conductive shield from copper or aluminum situated outside the armature; or h. with ferromagnetic yoke constituting the path for the main flux line; i. with external current source supplying the superconductive rotating winding via a ring-brush system.

Fig. 3 presents the structure of a magnetic and electric synchronous generator with a superconductive excitation winding against the background of a conventional generator.

4. Structural Characteristics of Generators with Superconductive Excitation Windings

4.1. Cryostat structure

The problem of a suitable cryostat structure for machines operating at low temperatures is extremely complex, since the cryostat must ensure not only minimal inflow of heat to the winding, but also possess suitable mechanical strength and rigidity.

The basic elements of rotating helium cryostats are: a. superconductive winding; b. supporting structure of winding; c. thermal shields; d. attenuating shield; e. coolant supply system; f. vacuum system; g. current supply conduit to excitation winding.

Figs. 4 and 5 present the structural designs of two versions of a rotating helium cryostat.

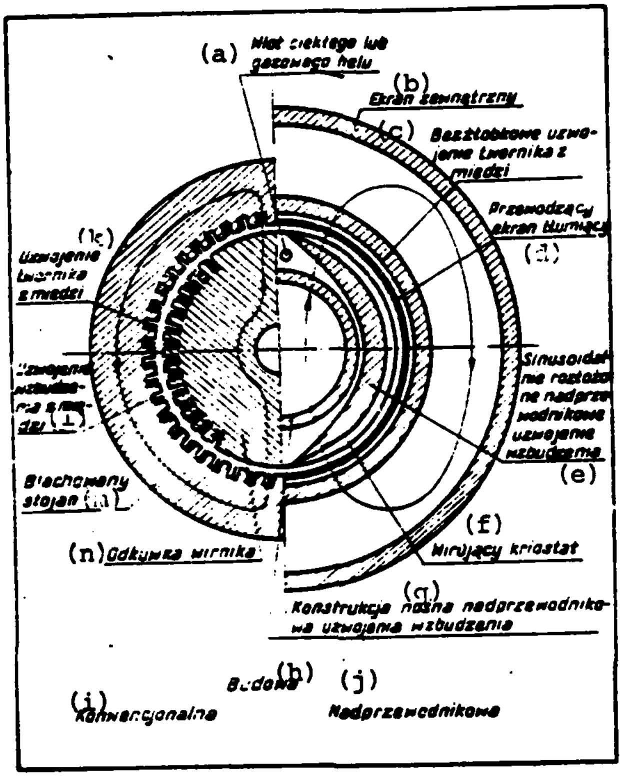

Fig. 3. Magnetic and electric circuit structure of synchronous generator (without ferromagnetic circuit from iron) with superconductive excitation winding (right side), against the background of a conventional generator (left side)

Key:

a. Liquid or gaseous helium intake
b. External shield
c. Smooth-core armature winding from copper
d. Conductive attenuating screen
e. Sinusoidally arranged superconductive excitation winding
f. Rotating cryostat
g. Supporting superconductive structure of excitation winding
h. Structure
i. Conventional
j. Superconductive /Key concluded on next page/

/Key to Fig. 3, concluded/

k. Armature winding from copper
l. Excitation winding from copper
m. Sheetmetal plate stator
n. Rotor forging

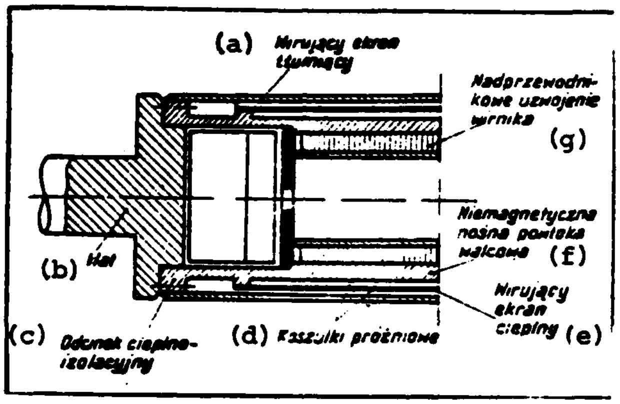

Fig. 4. Structural design of rotating helium cryostat in experimental model of synchronous generator P = 200 kW, Elektrotyazhmash, Kharkov

Key:
a. Rotating attenuating shield
b. Shaft
c. Heat-insulating section
d. Vacuum jackets
e. Rotating thermal shield
f. Nonmagnetic supporting cylindrical coating
g. Superconductive rotor winding

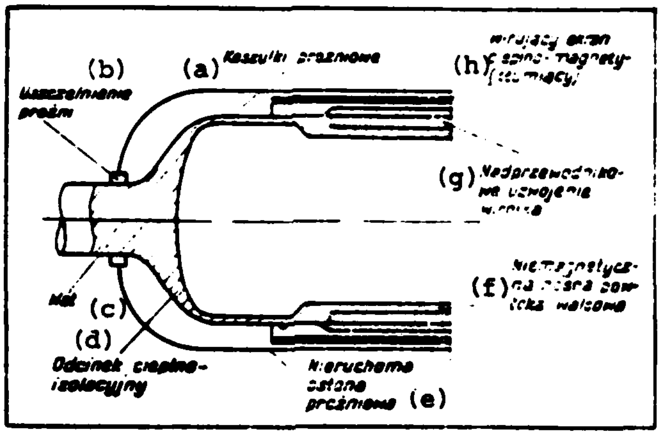

Fig. 5. Structural design of rotating helium cryostat in designs of high-power synchronous generator, S = 1000 MVA (Massachusetts Institute of Technology, MIT), United States

Key: a. Vacuum jackets
b. Vacuum seal
c. Shaft
d. Heat-insulating sector
e. Immovable vacuum shield
f. Nonmagnetic supporting cylindrical coating
g. Superconductive rotor winding
h. Rotating (attenuating) thermal-magnetic shield

Addendum a. The high current density ratings in a superconductive excitation winding on the order of magnitude $j_{exc} = 120$ A/mm^2 and the high magnetic field induction magnitudes $B_{exc} = 3$–5 T are the cause of the considerable electrodynamic forces acting on conduits. These forces may cause displacement of conduits or even result in destruction of superconductive windings and fastening structural elements. Deformation of an excitation winding may also be caused by mechanical stresses from centrifugal forces.

Particular attention should be focused on winding configurations providing reliable and effective cooling of the latter.

Addendum b. The supporting structure of a superconductive winding is usually designed in the form of a cylindrical coating made from a nonmagnetic material, for example, austenitic stainless steel with low saturability. In the front part, the supporting structure is connected to the rotor shaft by means of heat-insulating elements insulating the cryostat from the environment. Besides high mechanical strength (moment transfer), these elements must also be good heat insulators. Frequently these elements are cooled additionally by a cryogenic coolant.

Addendum c. Radial and axial thermal shields are used for protecting a low-temperature medium from external heat by way of radiation, tending to reduce the power supply of the cooling system. To obtain good heat insulation, they are usually surrounded by vacuum jackets (vacuum not below 10^{-5} mm Hg).

Addendum d. The attenuating shields made from a material which is a very good conductor of electricity (aluminum, copper) protect a superconductive excitation winding from variable magnetic fields caused by an asymmetric load and higher armature reaction harmonics and transfers the oscillatory torque in transient electric operational states of the machine, which can be one order of magnitude greater than occurs in the steady state.

The attenuating shield, rotating together with the rotor, can be situated in the "cold" or "hot" zone. By the cold zone, we mean that it is located near the cryostat. In small machines, the shield may be the external wall of the cryostat. In the case when a "cold" shield is used, the losses arising in it must be drained by the cryogenic fluid. In transient electric states, these losses may constitute a considerable load on the cooling system.

A "hot" shield is situated close to the armature winding and it can operate in the surrounding air temperature, or possibly be cooled by liquid nitrogen. Greater losses occur in a shield situated in the hot zone, the draining of which requires greater power consumption in the cooling system, however, at a temperature level which is more advantageous for the cooler.

Draining 1 W losses at a $77^{\circ}K$ temperature consumes an amount of power which is one order of magnitude less than that consumed in a helium cooler during draining of the same losses from a $4.2^{\circ}K$ temperature level.

The MIT design of the S = 1000 MVA generator in the United States envisions replacement of thermal and attenuating shields by the thermal-magnetic laminar shield presented in Fig. 6.

An alternate structural design of a synchronous machine with superconductive excitation winding proposes the application of a thermal, electric shield on bearings known as an inertial attenuating shield (Fig. 7). This shield can relieve the thermal-electric shield from the torque effect in transient electric operating states. During normal operation of the machine it has a rotating capability at a speed which is synchronized with the rotor.

Addendum e. Supply of helium and draining of used-up gaseous helium takes place on one side of the machine through the rotating system with a labyrinth type seal. Application of magnetic-liquid seals is envisioned for the generator (P_N = 500 MW) that is being designed in England. Liquid helium is supplied inside the rotor and from there it is directed via radial channels to windings under the effect of centrifugal forces. After it passes through the winding, the helium in the form of gas can be used for cooling electric conduits conducting excitation winding and slip-rings.

The refrigerating cycle must drain losses occurring in the winding from the variable component of the armature effect in the steady state. These losses may be small if the attenuating shield attenuates efficiently the variable fields permeating inside the rotor.

The losses in transient electrical processes may be very large and have a decisive effect on the selection of the cooling system. These losses result from fast flux and excitation current changes resulting from emergency operating regimes and sudden load changes.

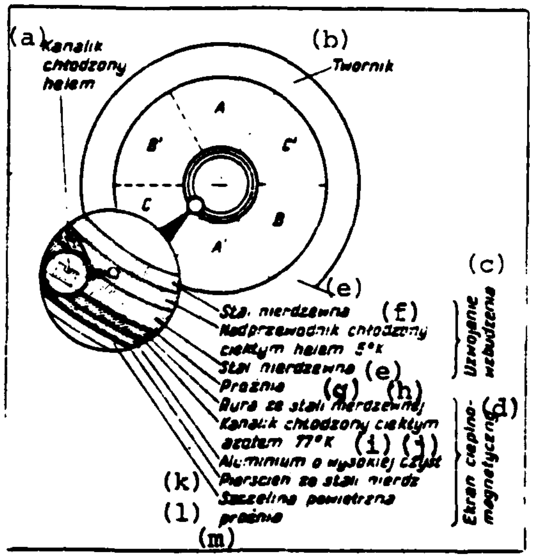

Fig. 6. Cross-section across rotor (excitation winding and thermal-magnetic shield) of synchronous generator, power S = 1000 MVA with superconductive excitation winding (MIT design), United States.
Remark: probably gaseous helium at 20°K will be used as the coolant of the thermal-magnetic shield

Key: a. Helium-cooled duct
b. Armature
c. Excitation winding
d. Thermal-magnetic shield
e. Stainless steel
f. Superconductor cooled with liquid helium, 5°K
g. Vacuum
h. Stainless steel pipe
i. Duct cooled with liquid helium, 77°K
j. High-grade aluminum
k. Stainless steel ring
l. Air gap
m. Vacuum

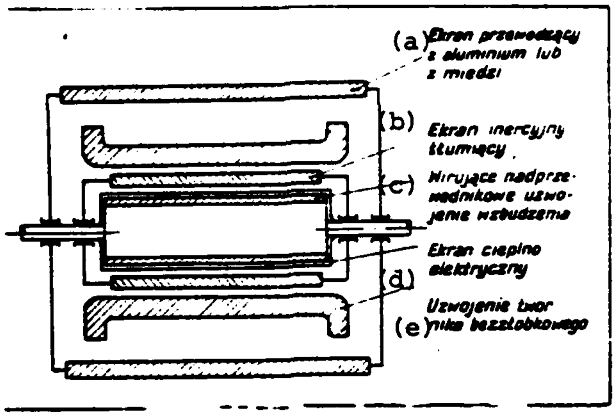

Fig. 7. Design of synchronous machine with superconductive excitation winding with inertial attenuating shield

Key: a. Conducting shield from aluminum or copper
b. Inertial attenuating shield
c. Rotating superconductive excitation winding
d. Thermal-electric shield
e. Smooth-core armature winding

Heat can also penetrate the cryostat from the surrounding environment. Most of the heat is checked by thermal shields.

Addendum f: For the purpose of reducing heat losses caused by external inflow of heat to the cryostat, some designs place the cryostat in a medium from which a vacuum on the order of at least 10^{-5} mm Hg is constantly evacuated.

4.2. Structure of armature winding

Application of a smooth armature core winding requires solution of a number of design-technology problems. The entire magnetic flux permeates through the winding wires in a grooveless machine, which makes it necessary to use quads transposed from wires with small cross-sections to reduce additional losses in the quads. The torque is transferred directly through the armature

winding. Requirements pertaining to fastening the active and front part of the armature windings necessitates structural designs in which the winding constitutes a single monolith. Plastics or possibly laminar wooden materials in the form of plywood, etc., are used.

From the standpoint of insulating material expenditures, a grooveless winding is more cost-efficient, since it does not necessitate the use of reinforced main insulation. The latter creates possibilities for switching over to a higher rated voltage.

4.3. External shield

The basis purpose of the external shield is to organize the space outside the armature in which a strong magnetic field occurs.

Three shielding possibilities are envisioned, using: a. a laminar ferromagnetic shield (magnetic yoke); b. a cast ferromagnetic shield; c. a cast shield made from copper or aluminum, which is a conductor of electricity.

Selection of the type of shield in large synchronous generators is decided by economic considerations.

The use of a laminar iron shield is not acceptable due to its weight. Calculations made in International Research and Development (IRD) in England have shown that for a 500 MW generator, the weight of the shield is 400 t (losses about 450 kW) [6].

A laminar ferromagnetic shield (magnetic yoke) contributes to reducing the reluctance for the principal flux of the machine.

In the case of application of a cast (nonlaminar) ferromagnetic shield, the expected losses are on the order of magnitude 80 MW.

Conductive aluminum or copper shields turned out to be most suitable. These shields will have a large diameter to reduce the losses in them, which in turn will entail an increase in the total volume of the machine. Eddy

currents in these shields decrease the resultant excitation flux in the machine. This may result in an elongation of the active part of the rotor, compared with a rotor furnished with a ferromagnetic shield.

Calculations made at IRD for the 500 MW generator demonstrated that a copper shield with a diameter equal approximately to 4 m and thickness 40 mm exhibits losses in the idle state on the order of magnitude 5 MW, which increase to 12 MW at a rated load with power factor $\cos \phi_{ind} = 0.85$.

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